1856 Embry-Riddle EagleSat 2 Report

Customer Team: Travis Imken, Embry Riddle EagleSat 2 Student Team
Facilitator: Alfred Nash
Session Date: February 21-22, 2017

- The work described in this presentation was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration
- The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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Systems

Jet Propulsion Laboratory

Study Name: 1856 Embry Riddle EagleSat

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Overview

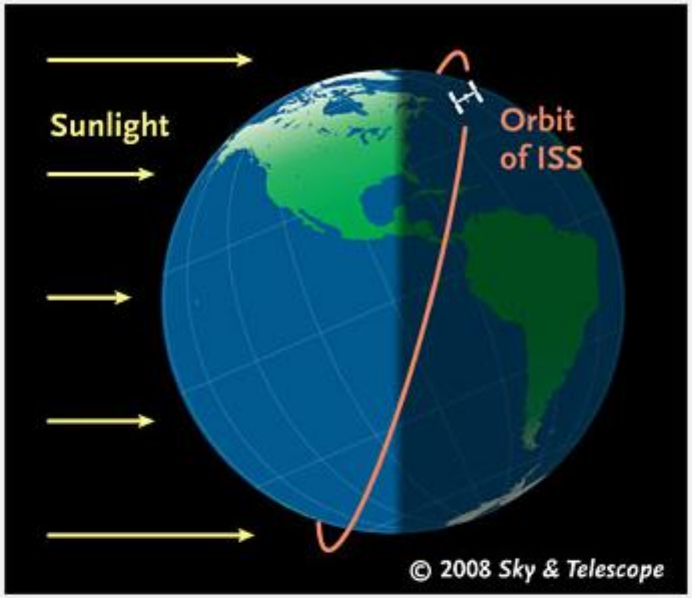
- Educational CubeSat mission proposing to CubeSat Launch Initiative in November 2017
  - Results of this study could contribute to required feasibility assessment
- Proposed mission was to:
  - *Detect and survey small-scale space debris*
    - → De-scoped during the study; instrument and concept maturation required
  - Detect cosmic rays and measure their properties.
  - Measure the effects of solar radiation on random access memory (RAM)

Design Requirements

- Fly two payloads:
  - Charged particle detector
    - → Pointing/FOV requirement: must face away from earth
    - → Either CMOS sensor or silicon charged particle detector
      - – Baselined CMOS, assumed interchangeable without impact to overall design
  - Memory degradation experiment
- Data collection
  - Charged particle detector: 8 Mb per orbit
  - Memory degradation experiment: 2.25 Mb per orbit
- Baseline ISS resupply orbit
  - Desired operational lifetime: >1 year
- 3U volume with Nanoracks deployer
  - 4 kg mass depending on vendor/waiver process

Orbit

- Baseline ISS Resupply Orbit:
  - Altitude: 402 km x 424 km
  - Inclination: 51.6 degrees
  - Period: 93 minutes
  - Eclipse Duration: 35 minutes (worst case)
  - ~7 Ground Station Passes per day
    - → Assume only 1 in a given orbit
    - → Constrained by power to transmit in sunlight only

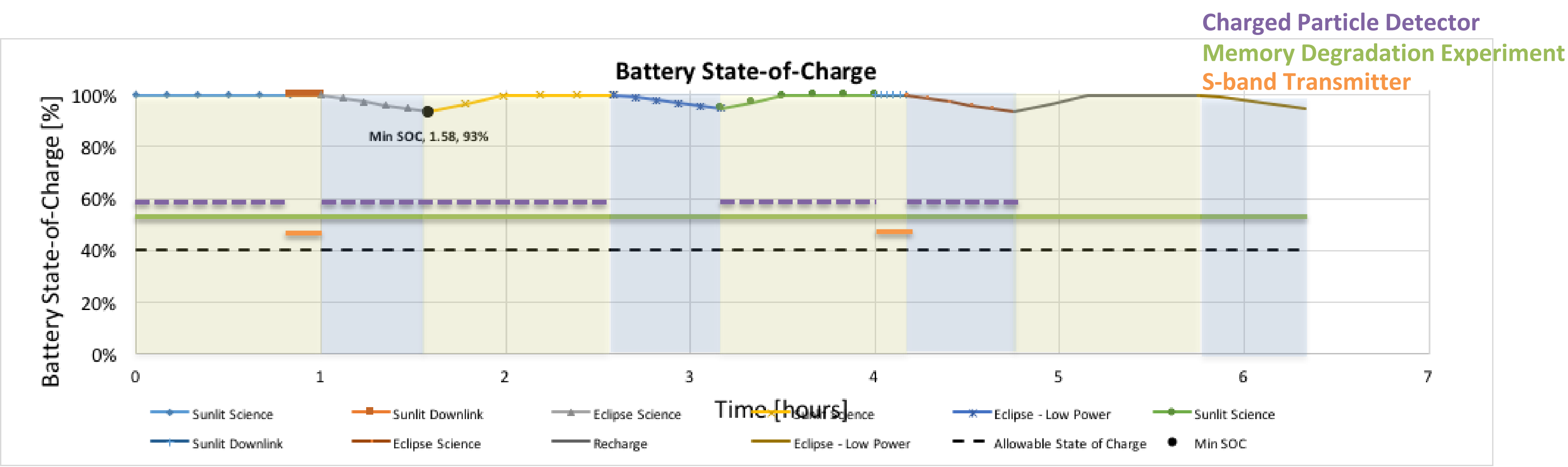


For a few days each May, the orbital plane of the International Space Station closely follows Earth's day-night terminator, which keeps the spacecraft in near-constant sunlight.

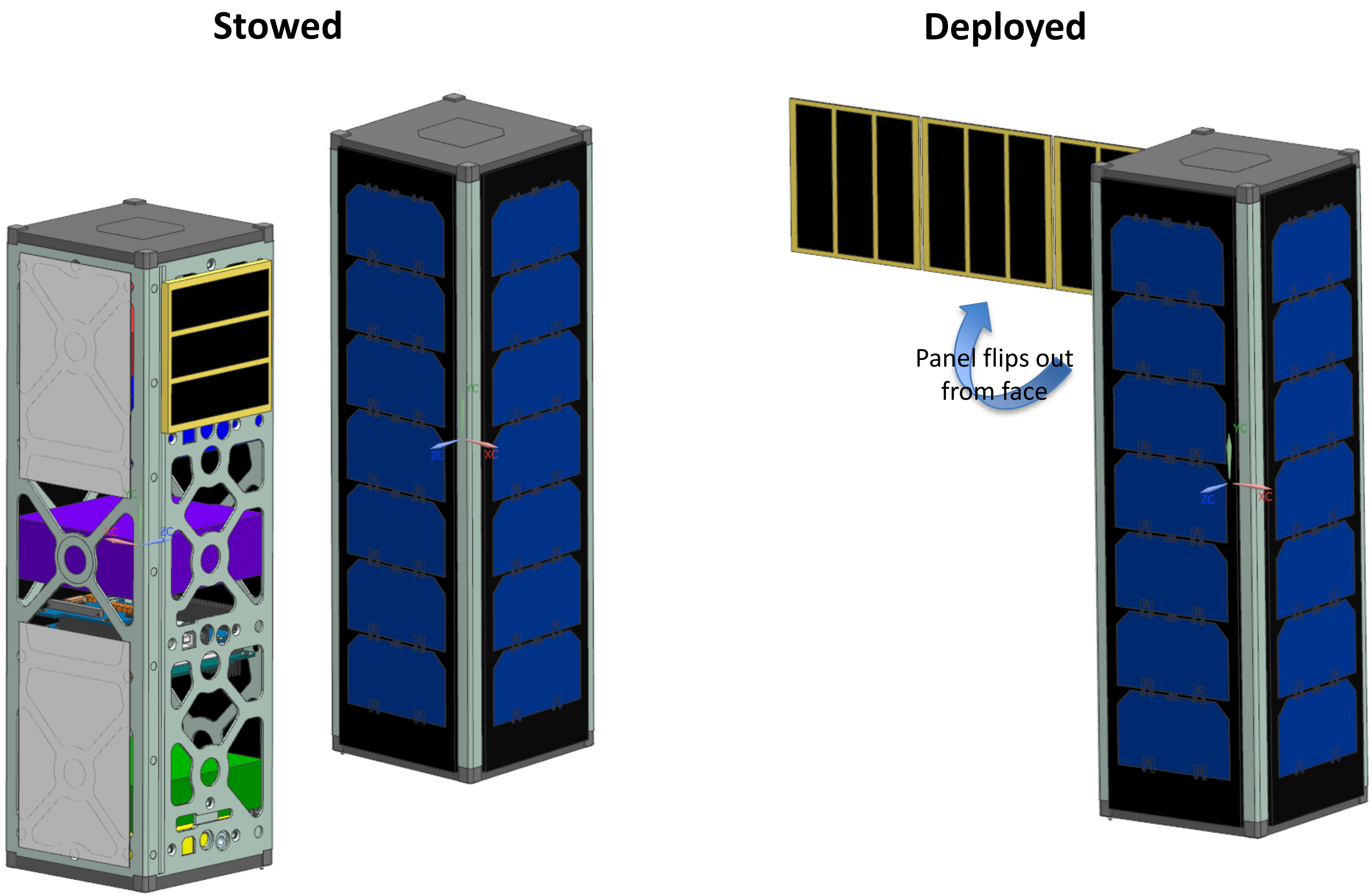
S&T: Gregg Dinderman

ConOps

- Charged Particle Detector: 50% duty cycle (10 minutes on, 10 minutes off)
  - Nominally turned off during low-power and transmit events - will be informed by improved knowledge of power and comm system architecture
- Memory Degradation Experiment: always running
- Modes of operation:
  - Science
  - Downlink
    - → Only during sunlight
  - Low-power (eclipse)
  - Recharge
- Power system margin with deployed panel allows more flexibility for customer in defining operations

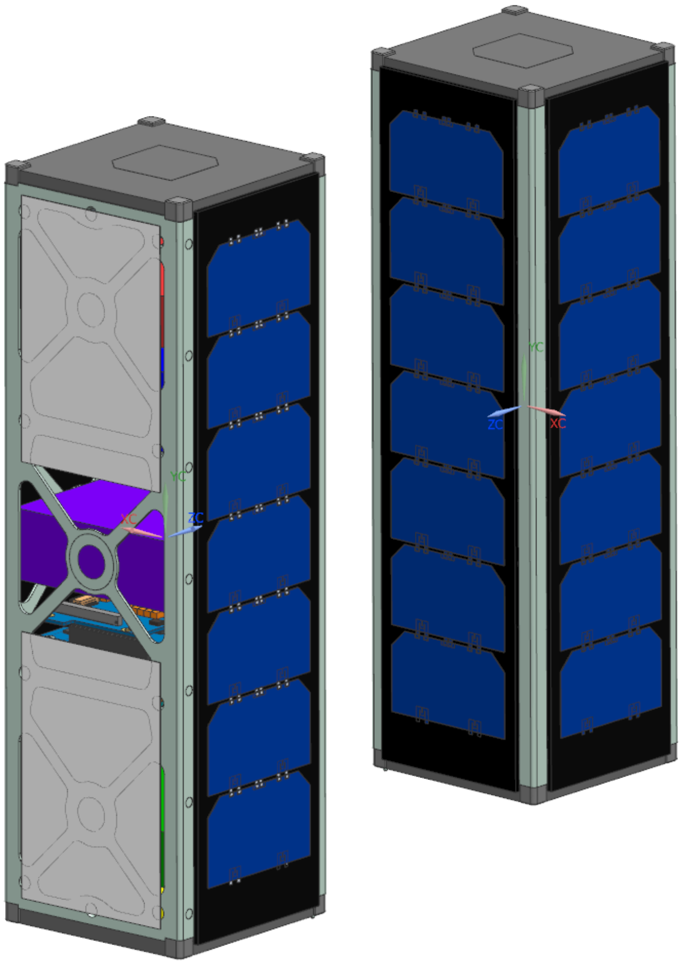


System Design – Power Option 1

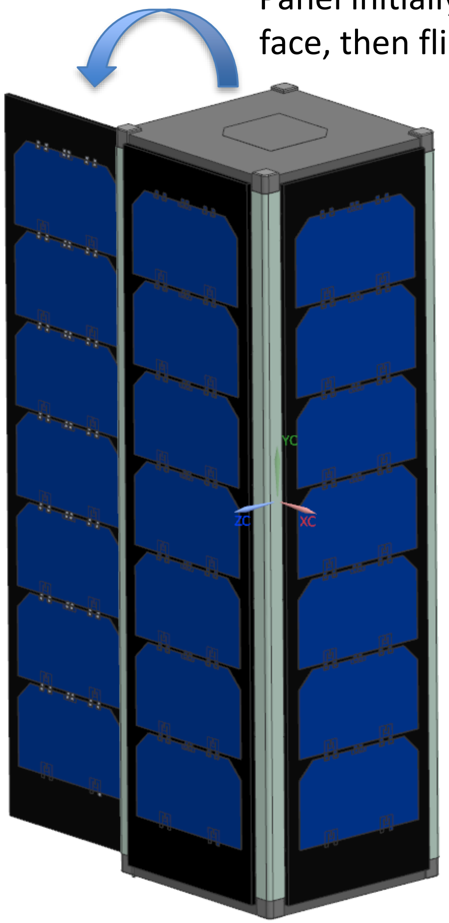


System Design – Power Option 2

Stowed

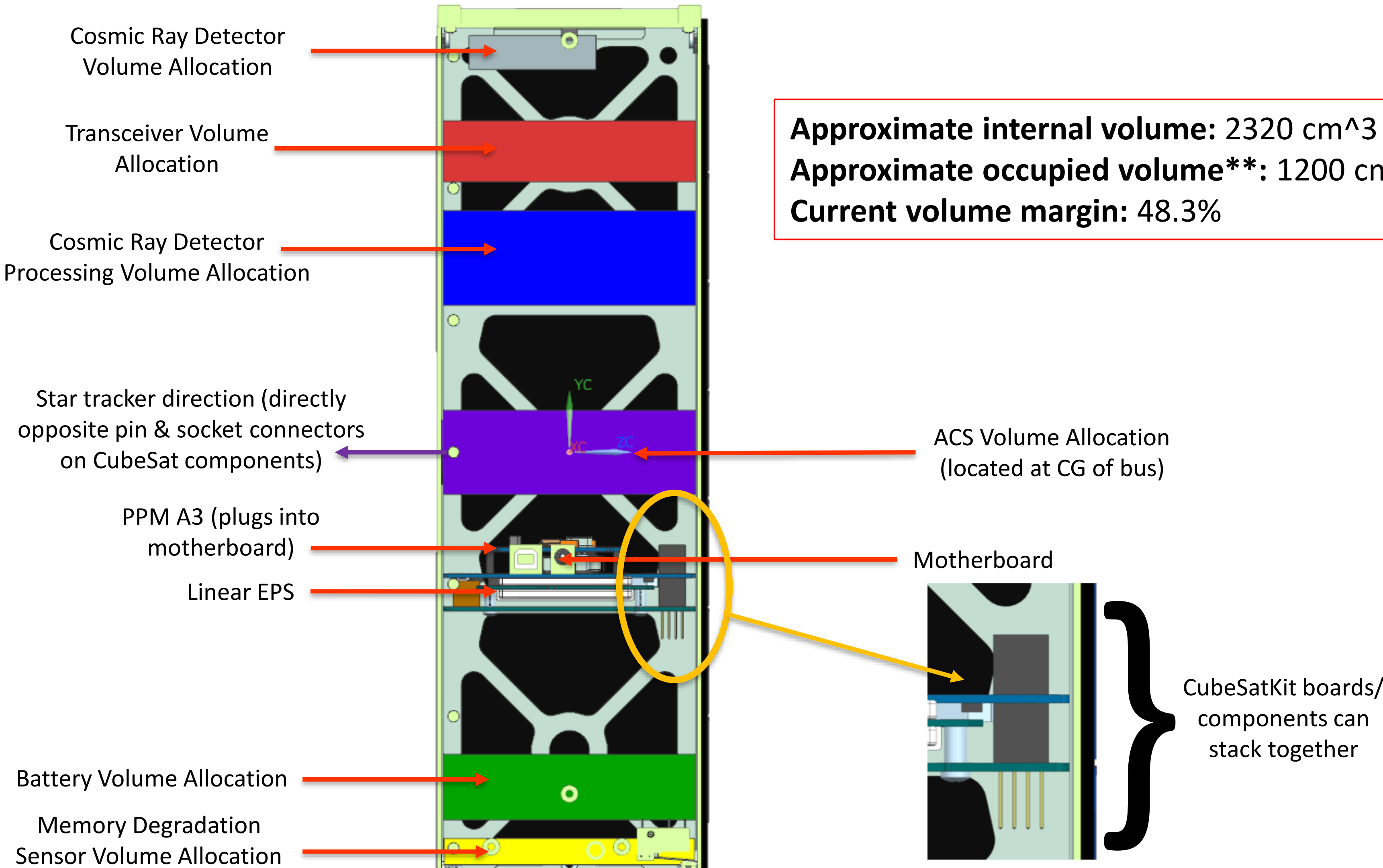


Deployed



System Design - Internal

Approximate internal volume: 2320 cm^3
Approximate occupied volume:** 1200 cm^3
Current volume margin: 48.3%



* Configuration subject to change

** Does not include cabling, mounting brackets, etc.

System Overview

- Instrument
  - Charged particle detector (CMOS)
  - Memory degradation experiment
- CDH
  - Pumpkin motherboard and processor
- ACS (~$100K based on analogs)
  - 3-axis stabilized
  - Integrated ACS system (3 reaction wheels, 3 torque rods, star tracker)
- Comm
  - UHF uplink (ENDUROSAT dipole), S-band downlink (ENDUROSAT patch antenna)
  - ENDUROSAT S/UHF transceiver
- Power
  - 1 deployed panel, 1 body-mounted panels OR 1 deployed panel, 2 body-mounted panels
  - Pumpkin EPS and battery pack (7.2 V, 5 Ah)
- Structure
  - Pumpkin 3U skeletonized structure

Mass and Power Roll-Up

LINK ☑

DASHBOARD

	Dry Mass Fraction %	CBE Mass (kg)	Subsys. Cont. %	MEV Mass (kg)	Mode 1 Power (W) Sunlit Science	Mode 2 Power (W) Eclipse Science	Mode 3 Power (W) Eclipse Downlink	Mode 4 Power (W) Recharge	Mode 5 Power (W) Eclipse - Low Power	Mode 6 Power (W) Sunlit Downlink
Power Mode Duration (hours)					1	0.58	0.17	1	0.58	0.17
PAYLOAD ON THIS ELEMENT										
Instrument	39.7%	1.17	30%	1.52	0.39	0.39	0.14	0.14	0.14	0.24
PAYLOAD TOTAL		1.17	30%	1.52	0.39	0.39	0.14	0.14	0.14	0.24
SPACECRAFT BUS										
Communications	9%	0.26	30%	0.34	2	2	5	2	2	5
C&DH	3%	0.10	2%	0.10	0.02995	0.02995	0.02995	0.02995	0.02995	0.02995
ACS	8%	0.25	30%	0.33	1.8	0.89	0.89	1.8	0.5	1.8
Power	29%	0.87	15%	0.99	0.006	0.006	0.006	0.006	0.006	0.006
Mechanical	10%	0.30	15%	0.35	0	0	0	0	0	0
BUS TOTAL		1.78	18.6%	2.11	3.84	2.93	5.93	3.84	2.54	6.84
TOTAL CBE					4.23	3.32	6.07	3.98	2.68	7.08
TOTAL MEV					43%	43%	43%	43%	43%	43%
					6.04	4.74	8.67	5.69	3.83	10.12

S/C DRY CBE

2.948		
0.68	23.1%	Subsystems

SPACECRAFT MEV (DRY)

3.63		
0.37	10.2%	Systems Cont./ NASA Margin

SPACECRAFT MPV (DRY)

4.00

SPACECRAFT MPV (WET)

4

SYSTEMS

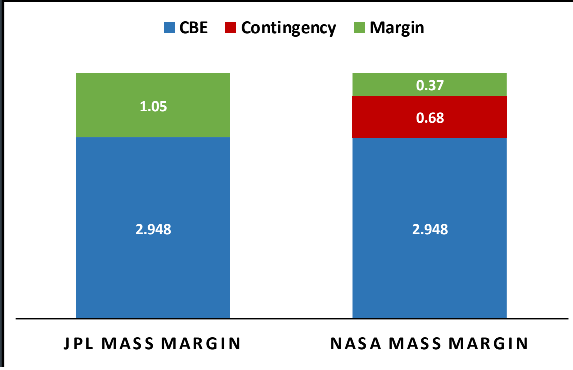
POWER CONTINGENCY	% alloc
43%	30%

initialize **DONE!**

JPL Mass Margin	
1.05	**26.3%**

NASA Mass Margin	
0.37	**10.2%**

ace



Legend

- Inputs from Subsystems
- Inputs from Systems
- Calculated (Protected Cells)*
- model ONLINE
- model HOLD (offline)

*No password req'd to unlock protected cells.

Design Rationale

- Commercially available (e.g. minimal customization) components
- Instrument accommodation (mass, configuration, pointing, power) does not drive requirements

Cost Summary

- Costs are notional hardware estimates only based on available data
- Costs do not include instruments, spares, labor, or facilities

- CDH + Structure: **$18.5K**
- ACS: **~$100K** based on analogs
- Comm: **$14.3K**
  - **$59.7K** for groundstation upgrade
- Power: **$22.1K** (Option 1) - **~$52.1K** (Option 2)

Options

- Power
  - Least expensive: CubeSat Shop fixed body mounted 3U solar panels with CubeSat Shop 3U deployable, higher implementation complexity
  - Most expensive: ClydeSpace 3U two panel deployable, lower implementation complexity
- ACS
  - Assumed design is likely very expensive and overdesigned
  - Alternate integrated systems are cheaper and offer flight heritage but require more power/volume
  - In-house piecemeal build is cheapest hardware option
    - → Reduced pointing authority
    - → Does not include processor or algorithms
- Comm
  - UHF transmitter would consume less power than S-band
    - → Possible way to reduce power system complexity
  - Trade for groundstation upgrade (higher datarate UHF vs S-band)
- Structure
  - COTS chassis is commercially available but offers less flexibility for mounting and accessibility during integration
  - Custom chassis requires more mechanical design effort but can offer more flexibility

Risks

- ✧ Instrument-specific processors and mounting interfaces are not accounted for in mass and cost estimates
- ✧ COTS components are not completely plug-and-play
  - Interface definition (data, mechanical, electrical, thermal) and management between several vendors is not trivial
- ✧ Thermal design was not considered
  - Batteries have strict operational range (above 0 deg C)
    - → Heaters likely necessary during eclipse (especially low-power mode)
  - Radio will tend to warm up significantly during transmit
- ✧ Orbit affects several aspects of design
  - ISS resupply orbit – precession, potentially limited operational life before de-orbit
  - Sun-synch orbit – more consistent operational profile, fewer available launch opportunities, slightly less benign radiation environment

ACS

Study Name: 1856 Embry Riddle EagleSat
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Subsystem Chair Phone: (818) 354-5305

Design Requirements

Parameter	Cosmic Ray Payload	Comm	Power
Control	N/A	~± 5 degrees	~± 1 degrees
Knowledge	~±5 degrees	N/A	N/A
Stability	N/A	N/A	N/A
Other	• Preferred not pointed at earth.	2 axis nadir pointing is enough. S-band antenna is 60 deg cone. UHF uplink nadir point is sufficient.	Assume sun tracking during re-charge period to maximize power accumulation

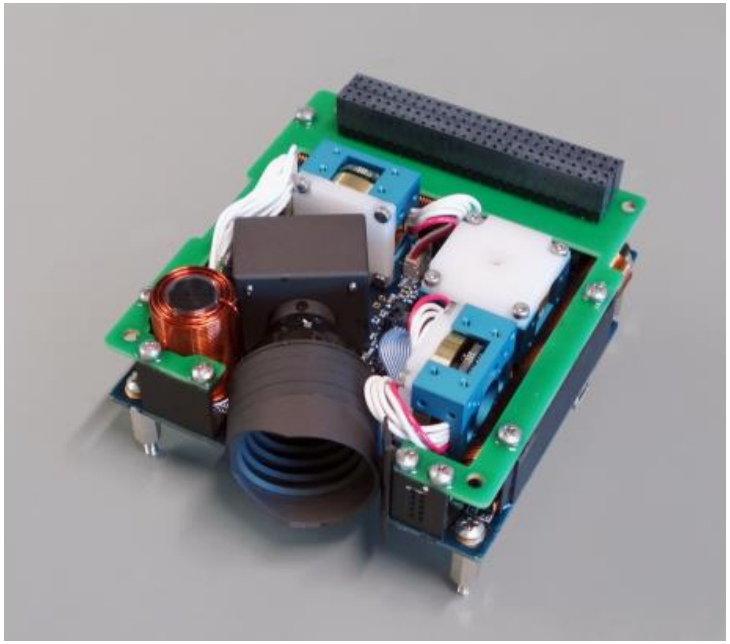
Note: All requirements are in 3-Sigma

SEU payload has no pointing requirements.

Design Assumptions

- 3U solid bus of 4 kg, no appendages
- 420 km circular orbit
- Earth avoidance accomplished by placement rather than ACS
- 3 axis is desired but not absolutely required.
- Better ACS performance improves power story
- Assumes "average" power specification for unit still provides enough capability to keep nadir point

- Selected Berlin Space Technologies iADCS-100
  - (https://www.researchgate.net/publication/260985245_iADCS-100_-_an_Autonomous_Attitude_Determination_and_Control_Subsystem_based_on_Reaction_Wheels_and_Star_Tracker_in_13U_Package)



- **CHARACTERISTICS**
- **Dimensions:** 95x90x32 mm³
- **Mass:** 250 g
- **Power (Nom./Peak):** 0.5 W / 1.8 W
- **Interface:** RS485, I2C
- **Operating Temperature:** -20°C to +40°C
- **Attitude Knowledge (Pitch&Yaw/Roll):**
  - **Pitch/Yaw:** 30 arcsec, 3 sigma
  - **Roll**: 200 arcsec
- **Attitude Pointing:** <<1°
- **Actuators:** 3 Reaction Wheels, 3 Magnetorquer
- **Sensors:** Star Tracker, 3-Axes MEMS Gyro, Magnetometer, Accelerometer

Design Rationale

- Selected iADCS due to the following reasons
  - Integrated system to minimize complexity for rest of the time
  - Lowest power
  - Smallest volume

Cost

- Cost of the iADCS is unknown. Could be very expensive due to the use of the star tracker. Other star tracker systems are ~$100K

- Other options are listed on options sheet.

Risk

- Berlin Space Technologies iADCS-100 is ~ TRL 4
  - Unit developed, but not flown

Option Comparison

- Selection of a integrated ACS COTS solutions only

Company Name	Unit Name	Mass	Volume	Peak Power	Average Power	ROM Cost	TRL
Maryland Aerospace	MAI-400	0.694	10x10x5.59	7.23	3.17	$35K - $50K	Flown
Blue Canyon Technologies	BCT XACT Lite	0.7	10x10x5	8	1.94	$50K - $100K ish	Flown
Berlin Space Technologies	iACDS-100	0.25	9.5x9.0x3.2	1.8	0.5	??	Not Flown

- Can add components and build the ACS in-house. Sample hardware set given below. No algorithms included or processor.

Component	Unit Name	Mass (kg)	Average Power	ROM Cost	TRL
Mag Torquer	MT01 Compact Magnetorquer	0.075 x 3	0.6W	$3K	Flown
Sun Sensor	nanoSSOC-D60 digital sun sensor	0.007	??	$4K	Flown
RWAs	MAI-400 wheel	0.09	0.85W (steady), 2.05 (tracking)	$21K	Flown

- References:
- http://spotidoc.com/doc/957797/bct-xact-datasheet---blue-canyon-technologies
- https://www.cubesatshop.com/product/mai-400-adacs/

Mechanical

Study Name: 1856 Embry Riddle EagleSat
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Subsystem Chair Phone: (818) 354-1888

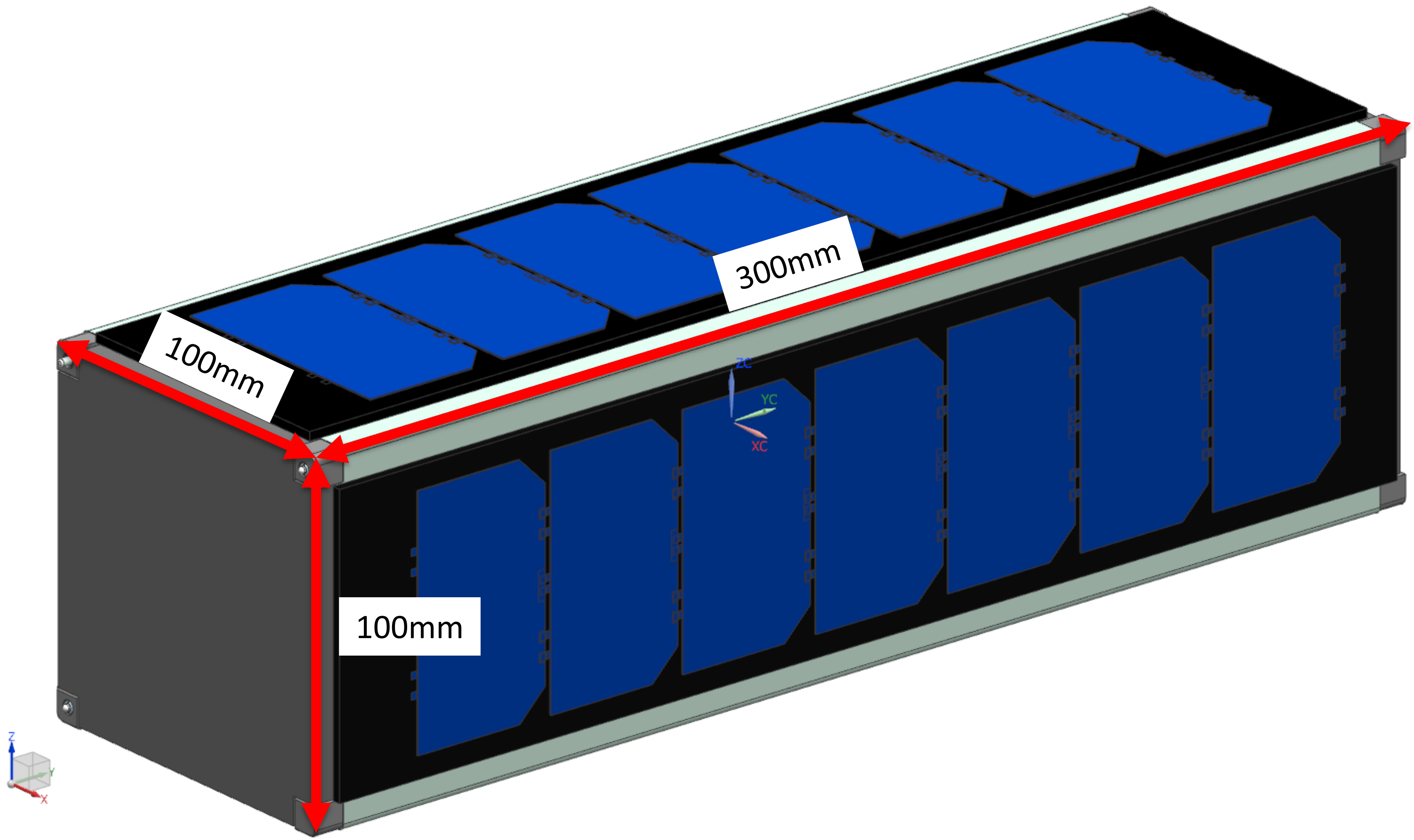
Design Requirements

- 3U COTS CubeSat bus
  - Accommodates on exterior the following components:
    - → 3X 3U solar panels (2X body-mounted, 1X deployable)
    - → 2X antennas (1X S-band patch, 1X deployable monopole or dipole)
  - Sufficient internal volume to accommodate payloads and essential comms/control/power/processing components
  - Compatible with standard CubeSat dispensers

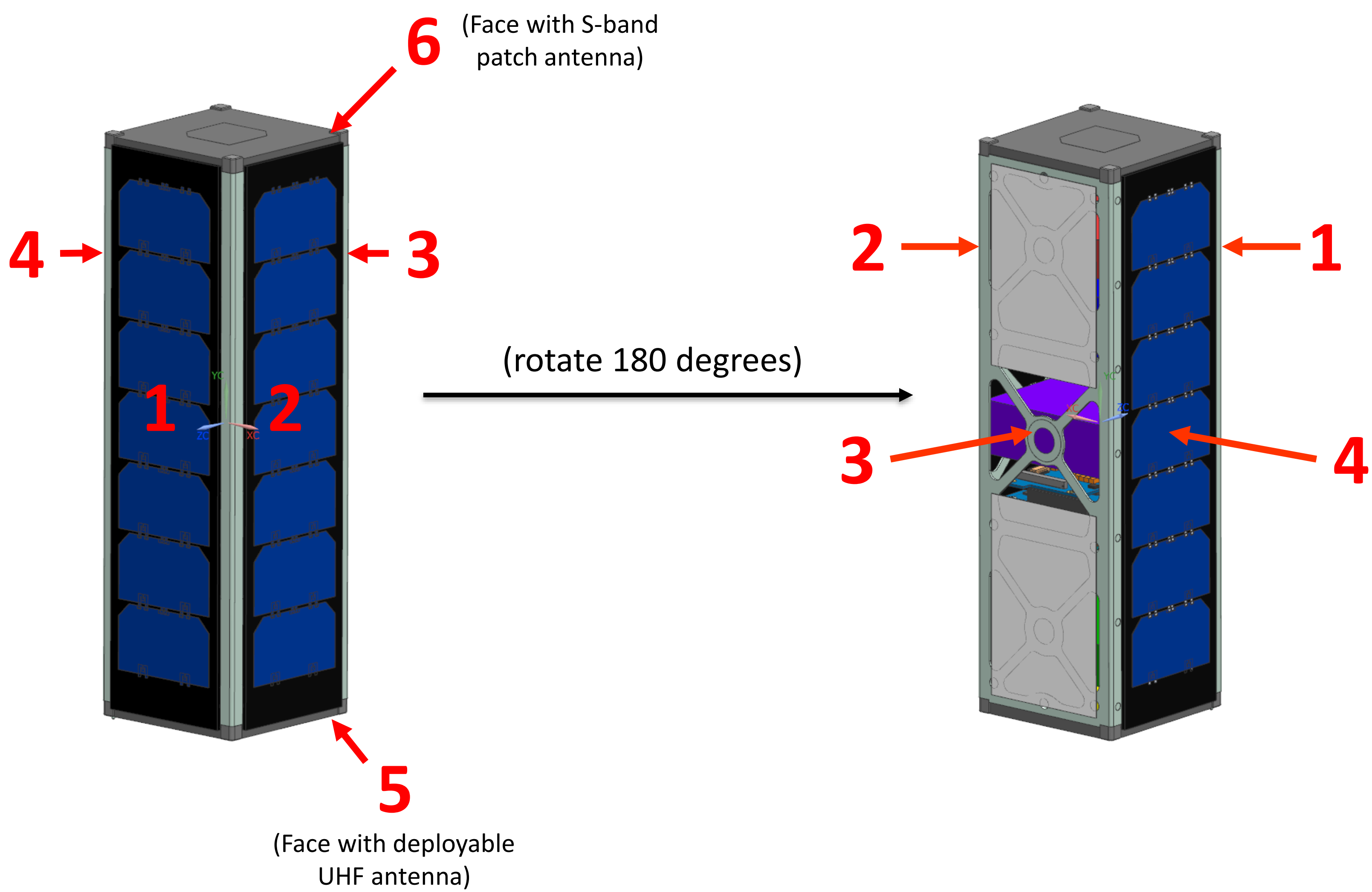
Design Assumptions

- Structure: 3U CubeSatKit Skeletonized bus (0.3kg)
- One deployable 3U solar panel
- Two body-mounted 3U solar panels
- Payloads can be located anywhere inside bus and their orientation won't affect data collection or science operations
- Constraints:
  - One face always points to cold space (for star tracker and radiator patches)
  - UHF and S-band antennas must be installed on opposite caps of bus
    - → Need to consider orientation during communication with ground station
    - → Could also consider alternate vendors or mounting options

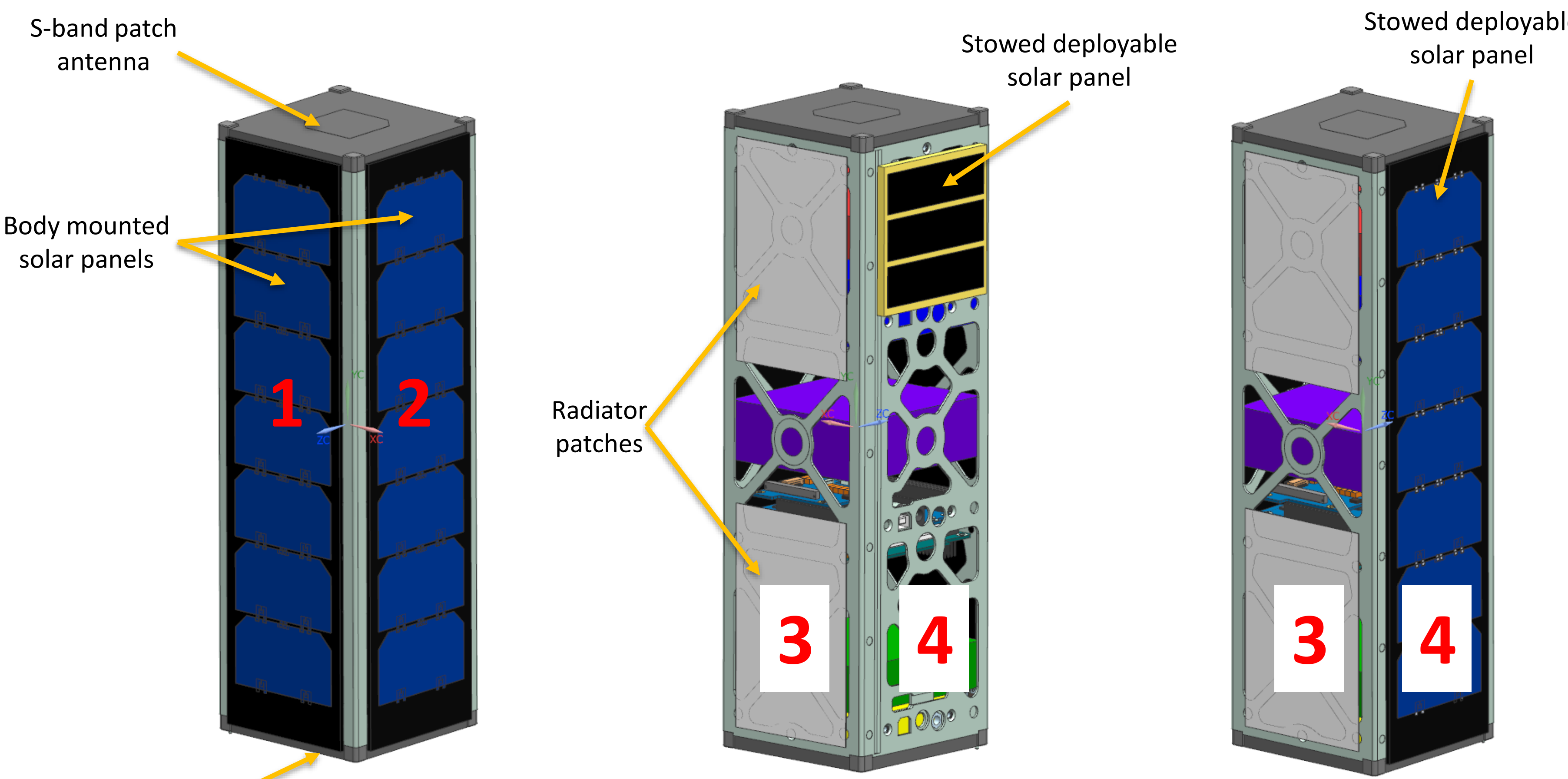
Overall Stowed Envelope



Face Legend


6
(Face with S-band patch antenna)
4
3
1
2
5
(Face with deployable UHF antenna)
(rotate 180 degrees)
2
1
3
4

Exterior Configuration (Panels Stowed)

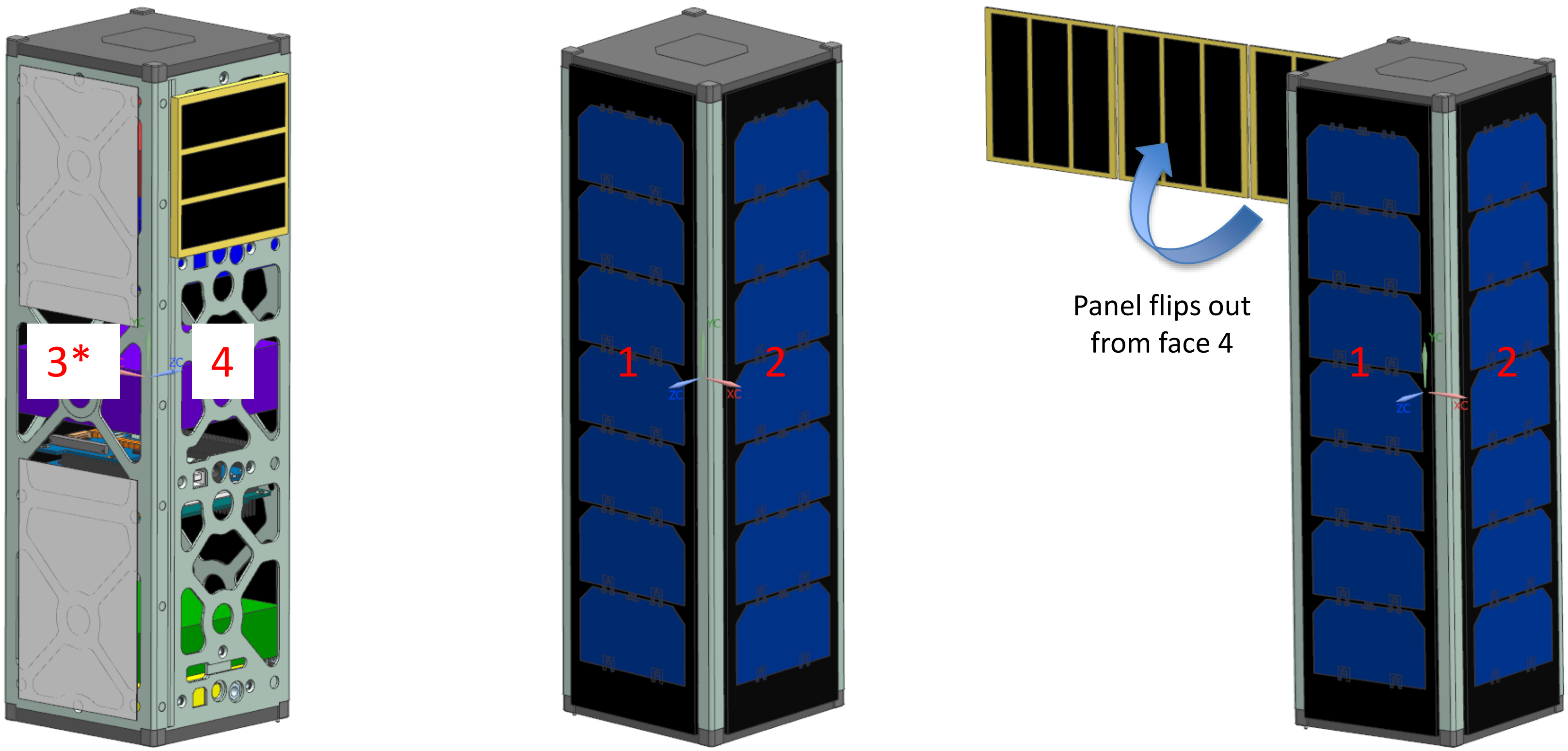


Low-cost solar panel option

High-cost solar panel option

Solar Panel Option 1 (Low Cost)

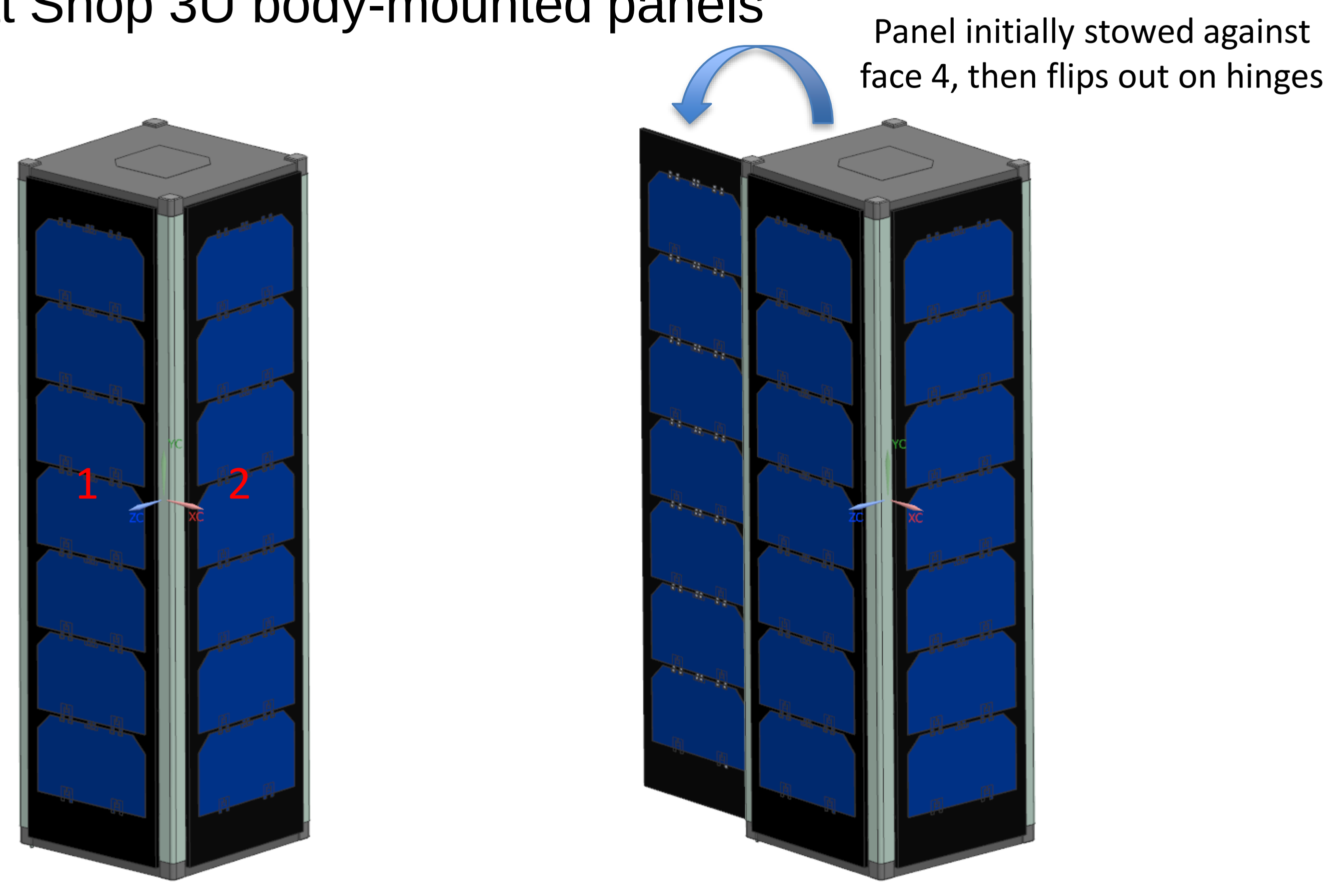
- 1X CubeSat Shop 3U deployable panel
- 2X CubeSat Shop 3U body-mounted panels



* Face 3 must always face away from Earth and the Sun because it hosts radiators and the star tracker (included in the baselined ACS module)

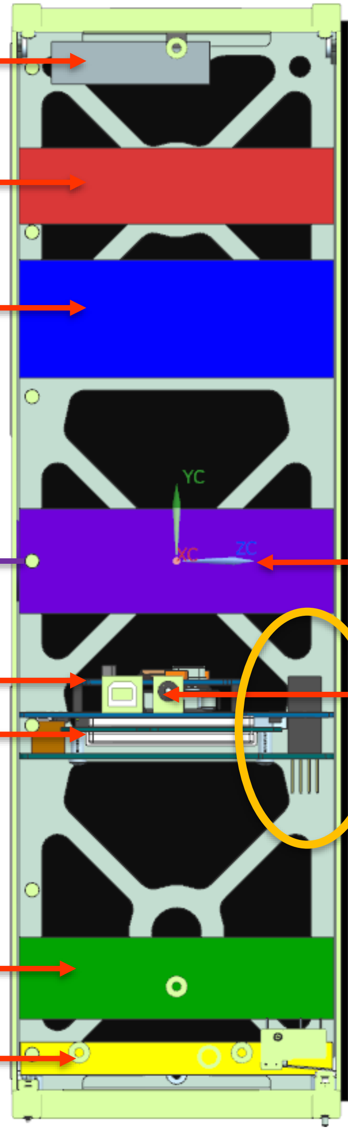
Solar Panel Option (High Cost)

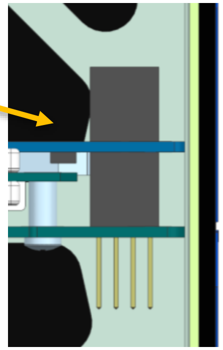
- 1X Clydespace 3U deployable panel
- 2X CubeSat Shop 3U body-mounted panels



Internal Configuration* & Volume Allocations

Approximate internal volume: 2320 cm^3
Approximate occupied volume****:** 1200 cm^3
Current volume margin: 48.3%





* Configuration subject to change

** Does not include cabling, mounting brackets, etc.

Design Rationale

- Pumpkin kit: includes chassis as well as some other components (processor, etc.), which may save some development time
- ACS is located at the center of the spacecraft (should technically be at the CG, but masses of many components are unknown at this time) for ease of control
- Three 3U solar panels fulfill power requirements, but one needs to be deployable so all three can see sun at the same time

Cost

- Pumpkin 3U CubeSat bus (skeletonized)
  - $8750
    - → Cost includes chassis, development board, motherboard, power supplies, protoboard kit, cables, tools, fasteners/mounting hardware, and various processor-specific components
    - → Source: http://www.pumpkininc.com/content/doc/forms/pricelist.pdf

Risk

- Thermal concerns: dissipating heat
  - Cannot turn face(s) with radiator patches toward sun
  - Some components are fairly power-hungry
    - → Need to sink heat from boards to bus, then radiate it out
  - Mitigation strategies:
    - → Deployable solar panel can help radiate some heat if the non-cell face is pointed at cold space
    - → Can couple boards to bus via wedgelock connections to facilitate conduction
      - – Can then radiate heat via radiator patches and cold-facing solar panel surface
- Solar panels
  - Cheap option: more hinges/articulations → more potential failure points
  - Costly option: might blow the budget
- May spend significant amounts of time debugging Pumpkin kit and making components cooperate with each other

Additional Comments

- Things to consider…
  - Couple components to the chassis to allow for heat conduction
  - Use non-sun-facing surface of deployable solar panel to radiate additional heat
  - Shuffle internal components around such that ACS is located at the overall system CG

Telecom

Study Name: Embry Riddle CubeSat

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Telecom Design Summary for the Customer

- The communication system design is a UHF/S-Band system and it is composed of:
  - ENDUROSAT S/UHF transceiver
  - ENDUROSAT S-Band antenna
  - ENDUROSAT UHF dipole
- The receiver is the Embry riddle station plus upgraded equipment to support the S-Band downlink
- The link analysis captures all the key parameters, including atmospheric losses and shows that 1 Mbps can be achieved.

Design Requirements

- **The CubeSat is required to download 25 Mbit per orbit**
- A quality of link/ BER (Bit Error Rate) of **10^-5** is required.

Design Assumptions-part 1

- Minimum Eb/N0 required is 9.6 dB uplink and downlink
- Downlink/uplink definitions:
  - Downlink: from CubeSat to Embry Riddle ground station
  - Uplink: from Embry Riddle ground station to CubeSat
- Frequency: S-Band (2.3 GHz) for downlink and UHF (437 MHz) for uplink
- Path length: path length is assumed between 400 Km and 2000 Km.
- **Receiver: Embry Riddle UHF station plus added S-Band capability.**
  - **S-Band dish size is 3 m (based on suggested commercial ground station to purchase)**
  - **UHF uplink transmitting power is 100 W.**

Design Assumptions-part 2

- Antenna noise temperature: 103-303 K depending on the frequency
- Receiver noise temperature: 290K.
- Atmospheric losses: minimal at both S-Band and UHF
- Additional losses (pointing, polarization) are also included.
- **Margin**: every link (downlink/uplink, best case/worst case) is designed with a margin of at least **3 dB.**
- Some of the link analysis assumptions (noise temperature, margin, additional losses, antenna gain) are selected on purpose to be **slightly conservative**: these results represents the worst case scenario.

Full Link Analysis Summary Chart

Item	Symbol	Units	Downlink Worst Case	Downlink Best Case	Uplink Worst Case	Uplink Best Case
EIRP:						
Transmitter Power	P	dBW	2.00	2.00	20.00	20.00
Line Loss/Waveguide Loss	L_l	dB	-1.00	-1.00	-1.00	-1.00
Transmit Antenna Gain (net)	G_t	dBi	8.30	8.30	15.50	15.50
Equiv. Isotropic Radiated Power	EIRP	dBW	9.30	9.30	34.50	34.50
Receive Antenna Gain:						
Frequency	f	Ghz	2.30	2.30	0.43	0.43
Receive Antenna Diameter	D_r	m	3.00	3.00		
Receive Antenna efficiency	η	n/a	0.66	0.66		
Receive Antenna Gain	G_r	dBi	35.38	35.38	0.00	0.00
Free Space Loss:						
Propagation Path Length	S	km	2,000.00	400.00	2,000.00	400.00
Free Space Loss	L_s	dB	-165.71	-151.73	-151.14	-137.16
Transmission Path and Pointing Losses:						
Transmit Antenna Pointing Loss	L_{pt}	dB	-3.00	-3.00	-1.00	-1.00
Receive Antenna Pointing Loss	L_{pr}	dB	-1.00	-1.00	-3.00	-3.00
Ionospheric Loss	L_{ion}	dB	0.00	0.00	-0.10	-0.10
Atmospheric Loss (H2O and O2 losses)	L_{atmo}	dB	-0.20	-0.20	0.00	0.00
Loss due to Rain	L_{rain}	dB	-0.10	-0.10	0.00	0.00
Implementation, additional losses		dB	-1.00	-1.00	-1.00	-1.00
Total Additional Losses		dB	-5.30	-5.30	-5.10	-5.10
Data Rate:						
Data Rate	R	bps	1,000,000.00	1,000,000.00	9,600.00	9,600.00
Data Rate	10 log(R)	dBbps	60.00	60.00	39.82	39.82
Boltzman's Constant:						
Boltzman's Constant	10 log(k)	dBW/(Hz*K)	-228.60	-228.60	-228.60	-228.60
System Noise Temperature:						
Antenna and Receiver Noise Temperature	T_{ant}	K	103.00	103.00	303.00	303.00
Sky Noise Temperature	Tsky	K	290.00	290.00	290.00	290.00
System Noise Temperature	T_s	K	393.00	393.00	593.00	593.00
System Noise Temperature	$10 \log(T_s)$	dBK	25.94	25.94	27.73	27.73
E_b/N_o		dB	16.33	30.31	39.31	53.29
E_b/N_o required		dB	9.60	9.60	9.60	9.60
Margin		dB	**6.73**	**20.71**	**29.71**	**43.69**

Design: Components selection

- The communication system design is an S-Band/UHF system composed of:
  - ENDUROSAT S-Band/UHF transceiver
    - → Mass: 114 g; Peak power consumption during transmission: 5 W (for 1.6 W power output), Receiving power consumption: 2 W* ; Volume: 9.2 x 2.52 x 0.6 cm.
  - ENDUROSAT UHF monopole antenna
    - → Mass: 85 g; Volume: 9.8 x 9.8 x 1.3 cm (stowed)
  - ENDUROSAT S-Band patch antenna
    - → Mass: ~65 g; Volume: 9.8 x 9.8 x 1.3 cm
- Information on antenna placement are under configuration.

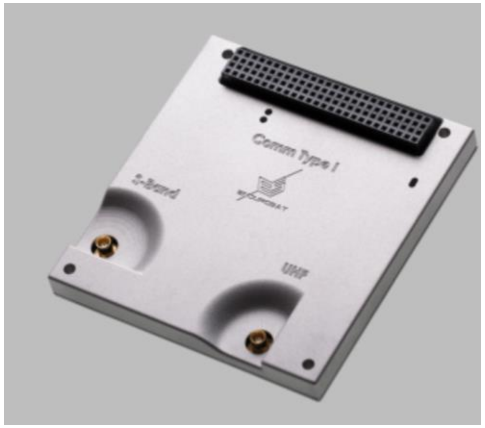
* Receiving power consumption is an assumption based on the peak and on typical values for similar components

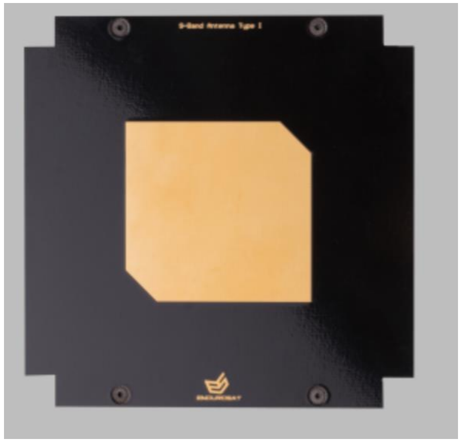
S-Band/UHF Radio and antenna components links

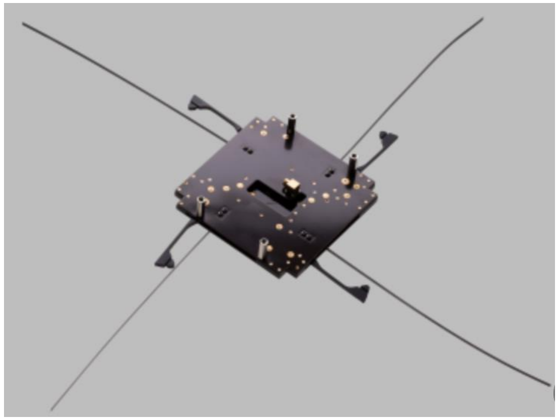
- S-Band Radio:
  - https://www.endurosat.com/cubesat-store/cubesat-communication-modules/transceiver-s-band_uhf/

- UHF Antenna:
  - https://www.endurosat.com/cubesat-store/cubesat-communication-modules/uhf-antenna/

- S-Band antenna:
  - https://www.endurosat.com/cubesat-store/cubesat-communication-modules/s-band-patch-antenna/

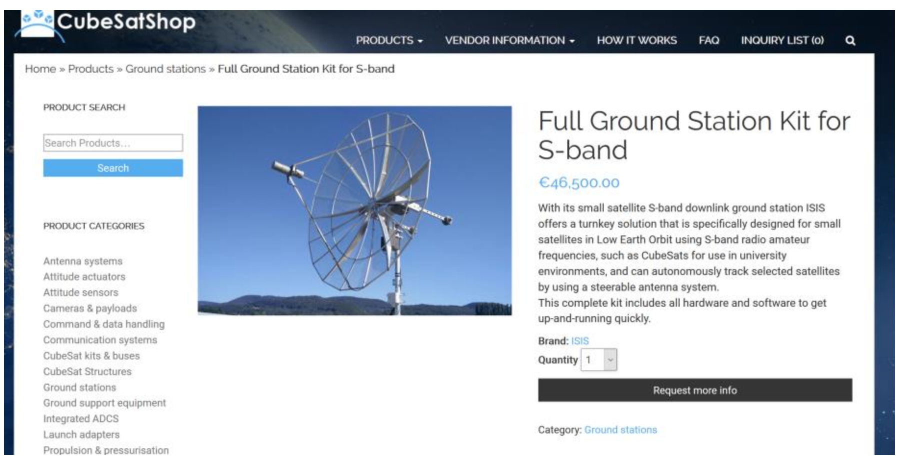


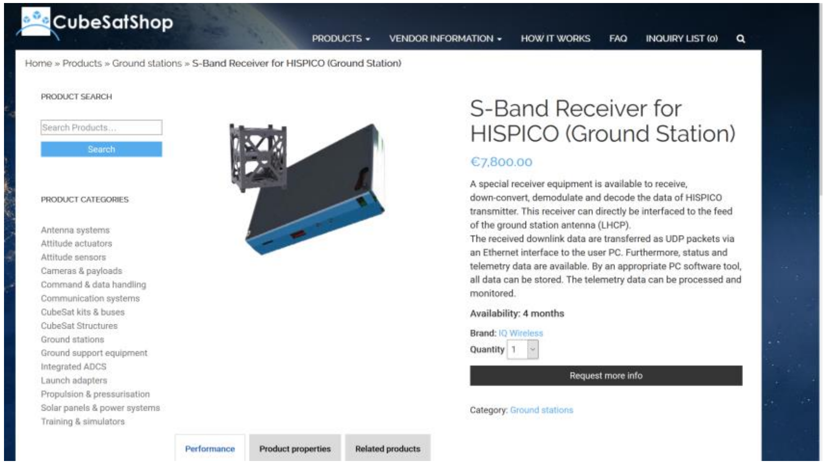




S-Band ground station upgrade (components and links)

- Suggested the ISIS S-Band package with a change of the receiver.
- The Hispico receiver is suggested as it will allow for 1 Mbps data rate.
- Links:
  - Ground station
    - → https://www.cubesatshop.com/product/full-ground-station-kit-s-band/
  - Hispico S-Band ground receiver
    - → https://www.cubesatshop.com/product/s-band-receiver-hispico-ground-station/





Cost

- The cost estimate for the components is:
  - Spacecraft: $14.3K (Transceiver: $7.7K, S-Band antenna: $3.3K, UHF antenna: $3.3K)
  - Ground station: $59.7K (Station: $51.15K, Upgraded S-Band receiver: $8.58K)
- The cost estimate **does not** include:
  - Cost of labor for:
    - → testing of the antenna and transceiver,
    - → Flight software and integration

Risk

- If data volume increases, 1 Mbps may not be sufficient to download all the data. However, right now the system has sufficient margin.

Power

Study Name: 1856 Embry Riddle
Subsystem Chair Name: Andrew Mitchell
Subsystem Chair Email: andrew.w.mitchell@jpl.nasa.gov
Subsystem Chair Phone: (818) 354-0672

Design Requirements

- Mission:
  - Orbit remains at 1AU distance from the sun
  - Mission duration of about 2.5 years
- Power positive during recharge mission mode
- Provide sufficient max power to each of the CubeSat subsystems
  - C&DH: 0.02 W
  - ACS: 1.8 W
  - Payload: 0.39 W
  - Comm: 5.0 W
  - Power: 0.1 W

Design Assumptions

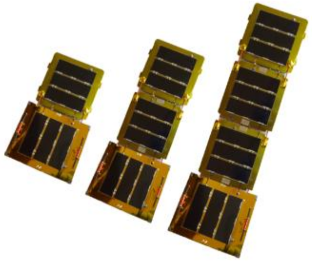
- General
  - 10% contingency applied to all power loads
  - Applied mass contingency ranges from 2% to 30% based on maturity of hardware and any modifications required
- Power Electronics
  - COTS power electronics
- Solar Array:
  - Solar array operating temperature
    - 60 C used for the solar array sizing
  - Solar array off-sun angle
    - +/-5 deg due to ACS pointing requirements
- Battery
  - Operating temperature of 20 C

Design: Power Electronics (1/3)

- CubeSat Kit Linear EPS
  - Capable of handling up to 15 W
  - Provides necessary voltages (Vbatt, 5 V, 3.3 V) for each of the S/C subsystems
  - No modifications necessary
  - Further research necessary to ensure design is spaceflight capable

Design: Solar Array (2/3)

- Solar Array (13 W BOL)
  - Least expensive: CubeSat Shop fixed body mounted 3U solar panels with CubeSat Shop 3U deployable, higher implementation complexity
  - Most expensive: ClydeSpace 3U two panel deployable, lower implementation complexity

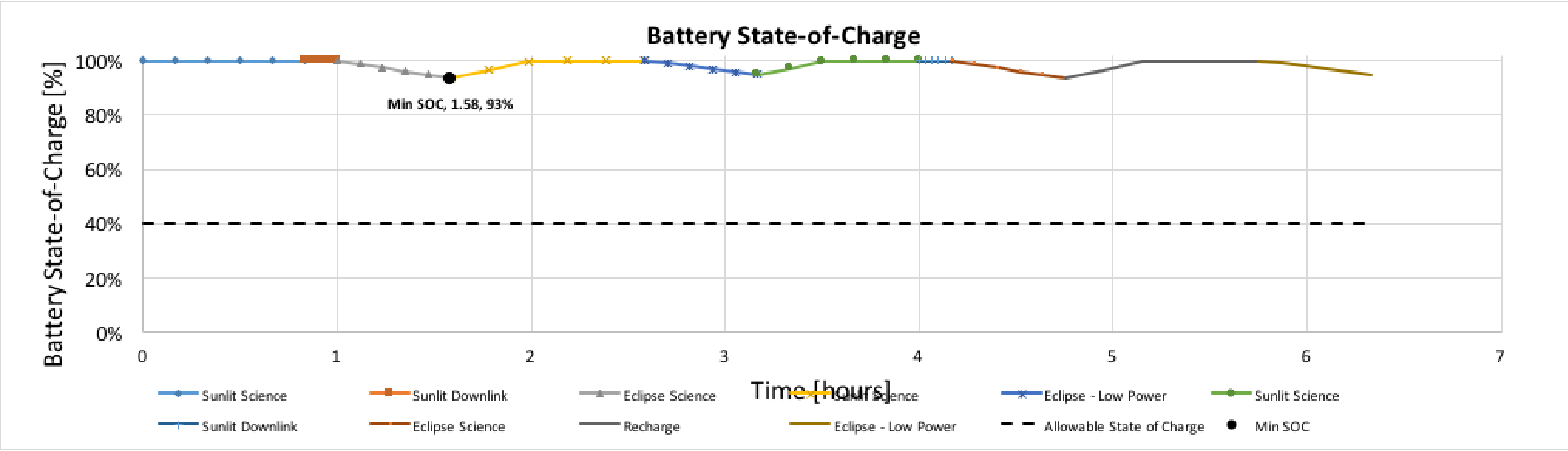


Array Sizing	
Solar Cell Type	Spectrolab UTJ
V_{mp} per cell at Design Temp [V]	2.35
I_{mp} per cell at Design Temp [A]	0.434
V_{oc} per cell at Design Temp [V]	2.66
I_{sc} per cell at Design Temp [A]	0.454
Maximum Power per cell at Design Temp [W]	1.02
Max Cell Width [cm]	3.97
Max Cell Length [cm]	6.91
Area per Cell [cm²]	26.62
Bare Cell Density [mg/cm²]	84
Total Number of Cells	33
Total Cell Area [cm²]	878.55
Manufacturing Loss Factor - Current [%]	98%
Manufacturing Loss Factor - Voltage [%]	98%
Manufacturing Loss Factor - Total [%]	96%
BOL Max Array Power at AM0, 28˚C [W]	**13.66**
Temperature Factor	
Operational Temp [˚C]	60.0
Design Temp [˚C]	28
V_{mp} Voltage Gradient [mV/˚C]	-6.5
I_{mp} Current Gradient [mA/˚C]	0.032
V_{mp} per cell at Operating Temp [V]	2.14
I_{mp} per cell at Operating Temp [A]	0.43
Temperature Factor [%]	**91.4%**
BOL Max Array Power at AM0, Op Temp [W]	12.48
Degradation and Losses	
Ultraviolet Loss Factor	98%
Radiation Loss Factor	96%
Thermal Cycling Loss Factor	98%
Micrometeoroid Loss Factor	98%
Operating Point Loss Factor	95%
LILT Loss Factor	100%
User-specified Loss Factor	100%
Temperature Factor [%]	91%
Lifetime Panel Degradation [%]	**78%**
EOL Array Power at Op. Temp. [W]	**10.71**

Design: Battery (3/3)

- Battery sizing energy of 5 Wh is driven by the sunlit science mode
- Requires at least one string of two cells in series
- CubeSat Kit™Battery Module 1 (BM 1)
  - 18650 battery cells, 2S2P, Vbatt = 7.2 V, 5 Ah
  - Relatively inexpensive option which fulfills energy requirements
  - Could explore using a smaller battery (2S1P)

Summary Information	
Driving Energy Requirement [W-hr]	15.00
BOL Energy Stored [W-hr]	37.00
Lifetime Battery Degradation [%]	100%
EOL Energy Stored [W-hr]	37.00
Number of Cycles	1000
Allowable Depth-of-Discharge [%]	60%
EOL Depth-of-Discharge [%]	41%
Nominal Voltage [V]	7.40



Design (3/3)

Subsystem MEL

Descriptor	Quantity	Mass CBE (kg)	Contingency	Total + Cont.
CubeSat Kit Linear EPS	1	0.16 kg	2%	0.16 kg
CubeSat Kit Battery Module	1	0.31 kg	2%	0.32 kg
ClydeSpace Deployable Twin Panel	1	0.40 kg	30%	0.52 kg
		0.87 kg	**15 %**	**0.99 kg**

Spacecraft PEL

	Mode Name	Sunlit Science	Eclipse Science	Eclipse Downlink	Recharge	Eclipse - Low Power	Sunlit Downlink
	Mode Duration [hours]	1.00	0.58	0.17	1.00	0.58	0.17
Carried Elements CBE Power [W]	Carried Element 1	0.00	0.00	0.00	0.00	0.00	0.00
	Carried Element 2	0.00	0.00	0.00	0.00	0.00	0.00
	Carried Element 3	0.00	0.00	0.00	0.00	0.00	0.00
Subsystems CBE Power [W]	Instruments	0.39	0.39	0.14	0.14	0.14	0.24
	Communications	2.00	2.00	5.00	2.00	2.00	5.00
	C&DH	0.03	0.03	0.03	0.03	0.03	0.03
	ACS	1.80	0.89	0.89	1.80	0.50	1.80
	Propulsion	0.00	0.00	0.00	0.00	0.00	0.00
	Thermal	0.00	0.00	0.00	0.00	0.00	0.00
	Power	0.01	0.01	0.01	0.01	0.01	0.01
	Mechanical	0.00	0.00	0.00	0.00	0.00	0.00
	Subsystem CBE Power [W]	4.23	3.32	6.07	3.98	2.68	7.08
	Contingency by Mode Override [%]	0%	0%	0%	0%	0%	0%
	Subsystems with Contingency [W]	4.65	3.65	6.67	4.37	2.94	7.78
	Distribution Losses [W]	0.14	0.11	0.20	0.13	0.09	0.23
	Converter Losses on Regulated Subsystems [W]	0.00	0.00	0.00	0.00	0.00	0.00
	Distribution Losses + Converter Losses [W]	0.14	0.11	0.20	0.13	0.09	0.23
	Total Power Required [W]	4.79	3.76	6.87	4.50	3.03	8.02
	Total Energy Required [W-hr]	4.79	2.19	1.15	4.50	1.77	1.34

Cost

- The following represent ROM estimates for the power subsystem

- Solar Array:
  - Option 1-Two CubeSat Shot Fixed Panels + Deployable: $20k
  - Option 2-ClydeSpace Two Panel Deployable: ~$50k

- EPS:
  - CubeSat Kit Linear EPS: $1K

- Battery:
  - CubeSat Kit Battery Module 1 (BM1): $1.1K

Opportunities

- Due to the small number of low-cost COTS power electronic options, the power subsystem is severely overpowered. With an increase in cost a battery subsystem and solar array design can be made to optimize the S/C power subsystem for additional mass savings.
  - Use a 2S1P battery instead of the 2S2P.
  - Use one body mounted panel + a small custom deployable

- If the radio is turned off during eclipse modes a two-panel body mounted solar array may be sufficient
  - Loss of spacecraft receiving ability is not ideal and could cause severe spacecraft control issues in the event of an anomaly

Risk

- The use of COTS power electronics as-is provides a cheap and easy implementation of the power system but also does not allow for any flexibility in changing the hardware.
  - Need high-load power margins to ensure changes in energy requirements do not break the power subsystem design
- Use of deployable solar panels adds complexity risk and mission operation risk
  - If the panel does not deploy successfully, operation of the S/C is severely limited

Command and Data Handling

Study Name: 1865 Embry Riddle EagleSat2
Subsystem Chair Name: Roger Klemm
Subsystem Chair Email: roger.klemm@jpl.nasa.gov
Subsystem Chair Phone: (818) 354-9379

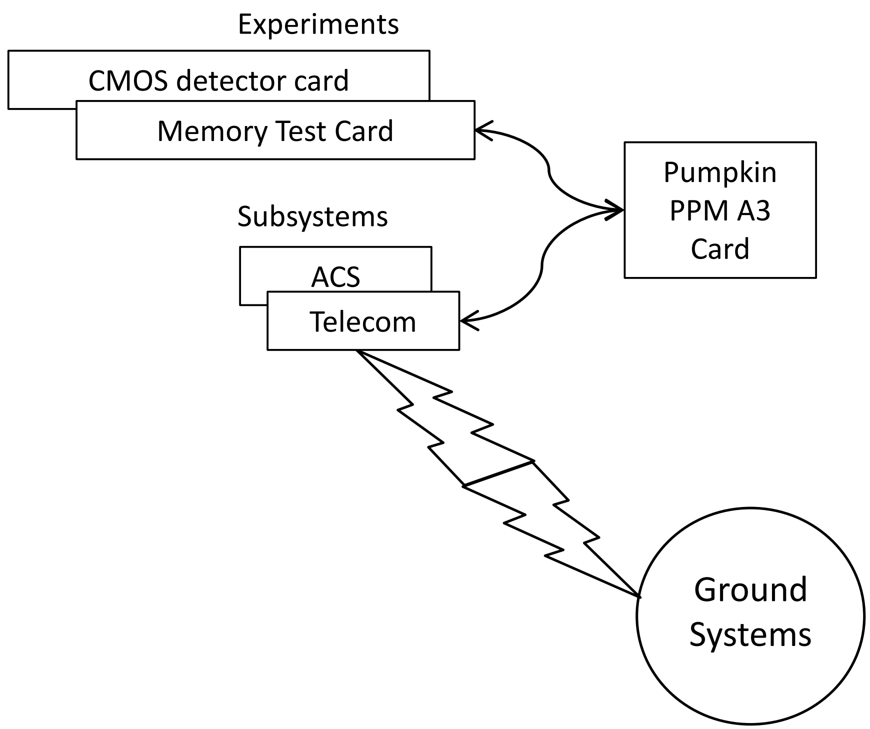
Design Requirements

- ✧ Operate in low earth orbit for one year
- ✧ Conduct two payload experiments
  - Detect and measure properties of cosmic rays
  - Measure effects of solar radiation on memory
    - → SRAM, FRAM, MRAM, EEPROM, Flash

Design Assumptions

- Use Pumpkin Cubesat computer components
  - Motherboard
  - PPM A3
- Experiments are custom cards
  - CMOS detector
  - Memory card
- Assume communications between cards on standard interfaces
  - Pumpkin supports several (I2C, UART, etc.)
- Use Pumpkin SALVO operating system
  - Various operations implemented by tasks in the flight software
  - Critical tasks (downlink, attitude control) set at higher priority than non-critical tasks (memory scan)

Design


Experiments
CMOS detector card
Memory Test Card
Pumpkin PPM A3 Card
Subsystems
ACS
Telecom
Ground Systems

Design Rationale

- Radiation Effects in space will be detected by scanning the target devices and comparing values to what is expected
  - When event occurs, record location (address), value, and time
  - Continuous scan at low cpu task priority enables timely detection of event while not impacting time-critical activities
  - In the CMOS sensor, an “event” would be a pixel with a high value
  - In the memory devices, an “event” would be a memory location with a value other than what was written there
    - → Different values should be written across the memory space, to detect bit flips in either direction (i.e., some bits set, some cleared)
- Suggest developing scheme for efficient conveying of experiment telemetry data. Consider dictionary with key/value association for
  - Channels (individual values) and
  - Event reports (occurrences)

Cost

- Parts from the Pumpkin catalog:

• 709-00332 MSP430 CubeSat Kit Software	5,500.00
• 711-00716 CubeSat Kit Upgrade to MSP430	4,150.00
• 11-00285 CubeSat Kit /MSP430, skeletonized, 3 U	8,750.00
• Total	$18,450.00

- Further work should identify in greater detail what parts need to be procured in order to develop and deploy the target system. There are many components in the Pumpkin catalog and it's not immediately clear exactly what parts are needed for complete system development.
- Software development is a separate body of work that is not costed
  - Some software can be inherited from previous efforts (EagleSat1)
  - Experiment algorithms may be obtained from related research efforts
  - Some software will have to be developed

Additional Comments

- Small Spacecraft Technology State of the Art paper from NASA Ames provides good survey of CubeSat components and capabilities:
  - https://www.nasa.gov/sites/default/files/atoms/files/state_of_the_art-aug2016.pdf

Ground Systems

Study Name: 1856 Embry Riddle EagleSat 2017-02

Subsystem Chair Name: Greg Welz
Subsystem Chair Email: gwelz@jpl.nasa.gov
Subsystem Chair Phone: (818) 393-4978

Design Requirements

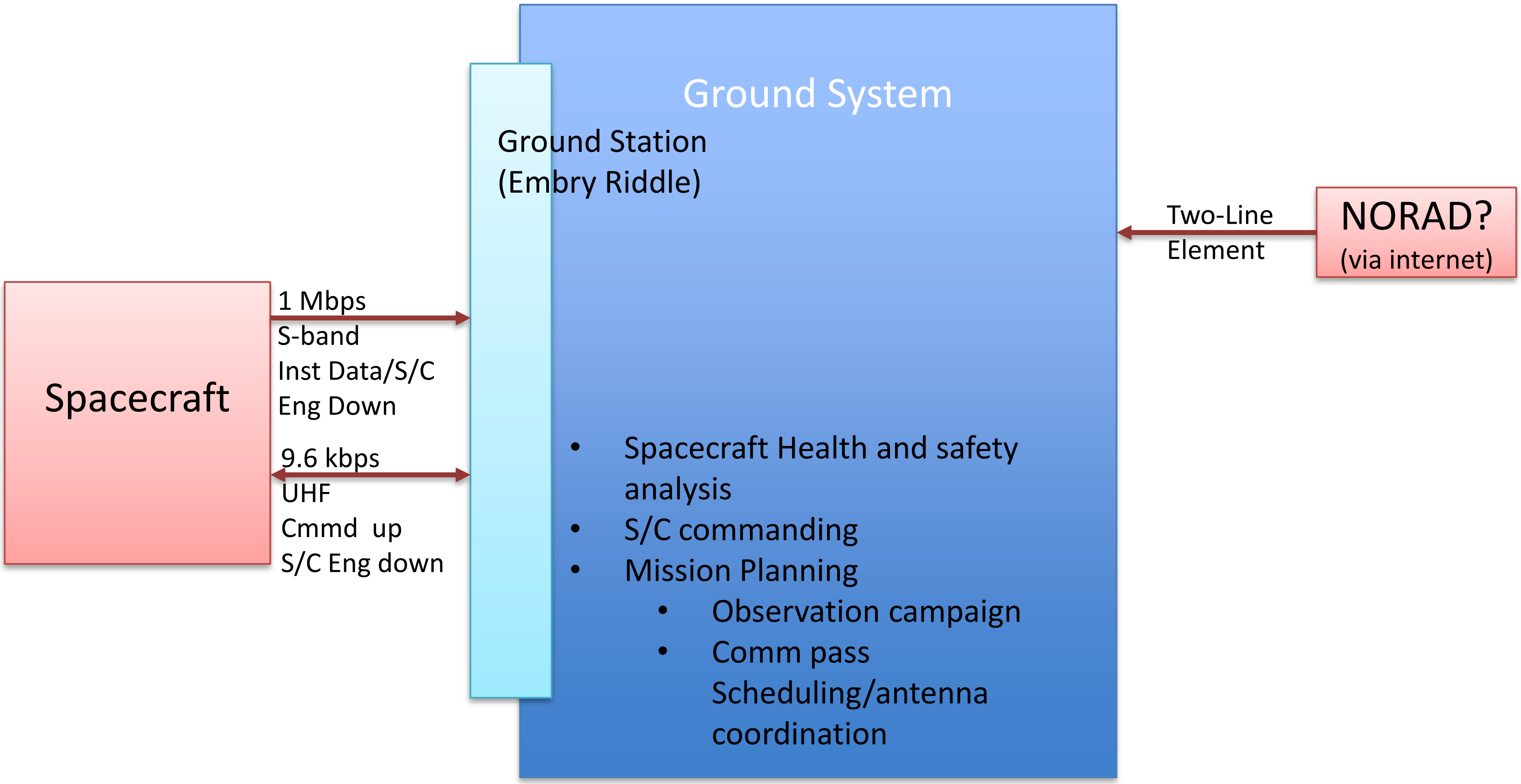
- Instruments collect 10.3 Mb of data per orbit, ~160 Mb/day
  - Based on 2 instruments (secondary and tertiary)
  - No latency requirements of note
- Telecom providing a UHF/S-band solution
  - UHF - 9600 bps for uplink/downlink,
  - S-band – 1.0 Mbps for downlink

Design Assumptions

- Orbit assumption was ISS like orbit
  - ~93 minutes per orbit
  - ~9 downlink opportunities day
  - ~7 minutes of link time per opportunity
- Nominally added 50% margin to daily data volume, this provides room for growth and protocol overhead.
- Given planned telecom design a day of data, plus margin, can be returned in 4 minutes, providing significant freedom in scheduling and managing links.
- Spacecraft activities all performed by FSW, enables simple commands
- Current telecom operations strategy:
  - The ground system polls the spacecraft to initiate the communications session
  - Ground coordinates the communications session
    - → Commanding, data downlink and re-transmission, clear memory, end session

Design

- Based on discussions the Ground Data System (GDS) will be built around the same GDS in use for EagleSat 1
  - This constrains/simplifies the FSW design to use the same command and telemetry formats as EagleSat 1
  - Augmentation to both the FSW and GDS would likely need to be made to support formats for the new instruments
- All operations performed at Embry Riddle by students
- Navigation information needed for coordination of tracking passes
  - Two-Line elements are adequate for this mission
  - Can be used in conjunction with science data to reconstruct approximate orbit region of bit flips, assuming short epochs for bit flip testing



Items in blue boxes are part of ground system design, all else fall outside

Design Rationale

- Keep cost low,
- Use existing solutions when possible

Cost

- Not applicable,
  - All implementation performed by students extending existing tools
  - Likely some small costs for computing hardware for testing and running the ground system and testbed,
  - Ground station costs provided by the telecom chair

Risk

- Moderate to low risk mission, as far as smallsat missions go
  - Smallsats by nature are risky simply because of the H/W used, as far as the ground system this is simple mission with significant inheritance
  - Operations has plenty of margins for data return and communications opportunity
  - No timeliness requirements of note
  - Little to no active control of S/C planned/needed/possible keeps operations simple
  - Beacon operations may not be possible with the radio selection
    - → Beacon is planned for post launch health detection
    - → Beacon like operations for some radios requires S/C to receive a modulated signal before it transmits. This can be handled by the GDS with support of TLEs to predict when the S/C should be in view of the ground station

Additional Comments

Notes and calculations

93.0	minutes/orbit
15.5	orbits/day
9.0	avg downlink opportunities per day
7	minutes avg downlink duration per opportunity
10.3	Mb per orbit
158.7	Mb per day
50%	margin on data volume and link
238.1	Mb per day budgeted for downlink
3780.0	seconds available downlink time
63.0	Kbps minimum downlink rate
1000.0	kbps via S-Band downlink
238.1	Seconds of downlink needed per day at S-band rate
4.0	Minutes per day needed for S-band rate